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GYROTRON DEVELOPMENT FOR SPACE POWER BEAMING

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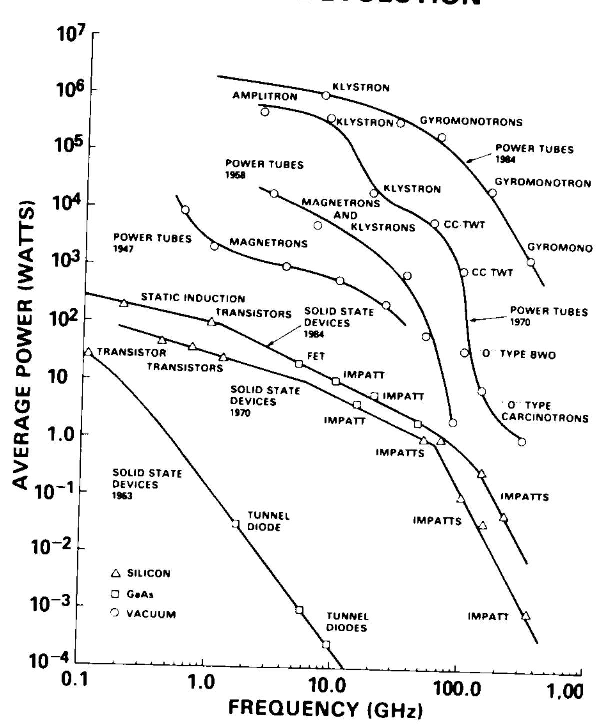
Earliest NASA mission for space power beaming is most likely the powering of a lunar orbiting power station. Assume the power station puts out 20 MW and beams the power over a 1000 km range. If the receiving and transmitting antenna have equal diameter D, the receiver must be in the near field of the transmitter, or

$$D^2 \approx (R\lambda/2)^{1/2}.$$

λ = 2 mm (140 GHz), D ≈ 30 meters

λ = 1 mm (300 GHz), D ≈ 20 meters

RF SOURCE TECHNOLOGY
HISTORICAL EVOLUTION



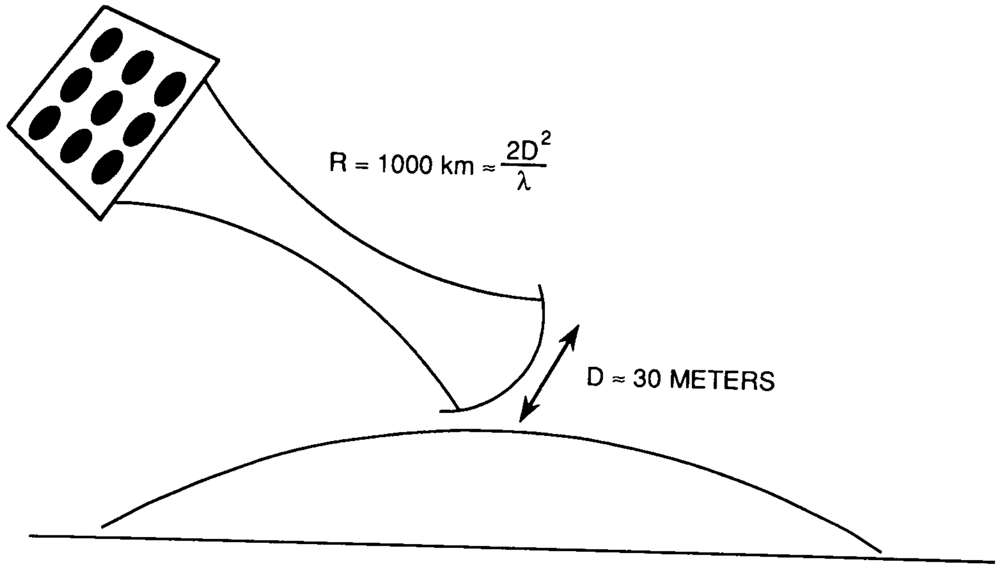
Gyrotron has, up to now, generated by far the highest average power at millimeter wavelength. Also, the beam voltage is relatively low (V_b < 100 kV) so it can be more easily used in a space based environment.

Consider a 50 element phased array, each element is 400 kW.

<u>Advantages of Phased Array</u>

* A 30 M antenna for 2 mm radiation is extremely difficult
* A single 20 MW tube would be very difficult
* A phased array allows some electronic steering of the beam
* A 50 element phased array at 400 kW each requires 4 meter dishes at 140 GHz and 2.8 meter dishes at 300 GHz
* A phased array allows for graceful degradation

140 GHz PHASED ARRAY SPACE POWER BEAMING FOR LUNAR MISSION AT A RANGE OF 1000 km

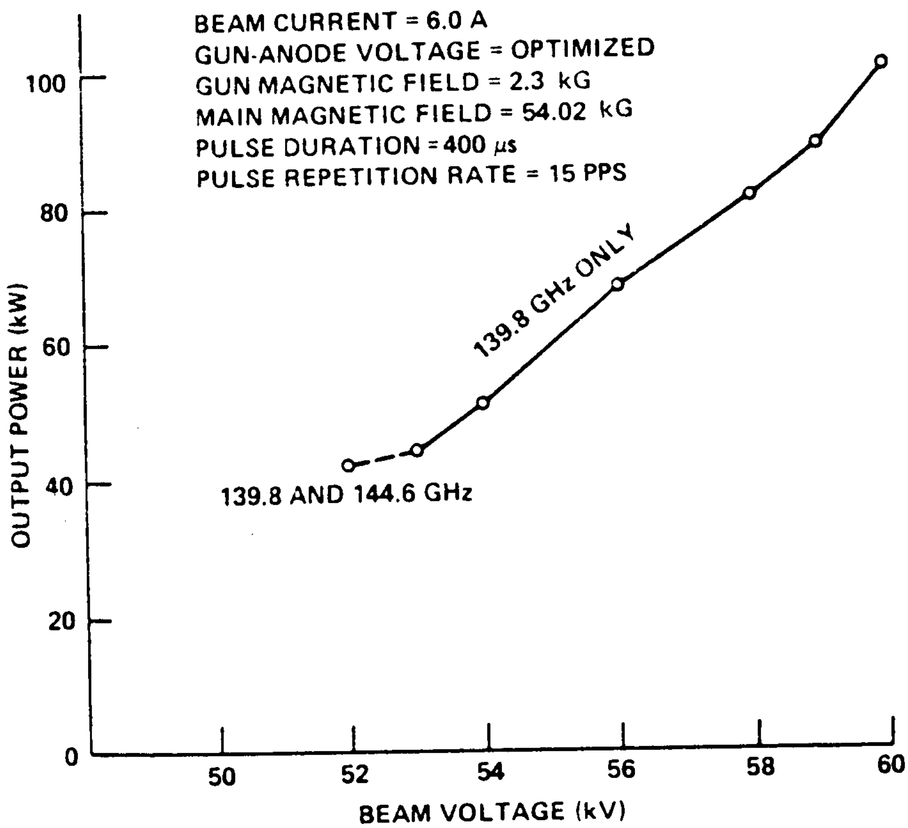


There are two crucial elements to the NASA application from the point of view of the millimeter wave source:

* **Generating the Power**

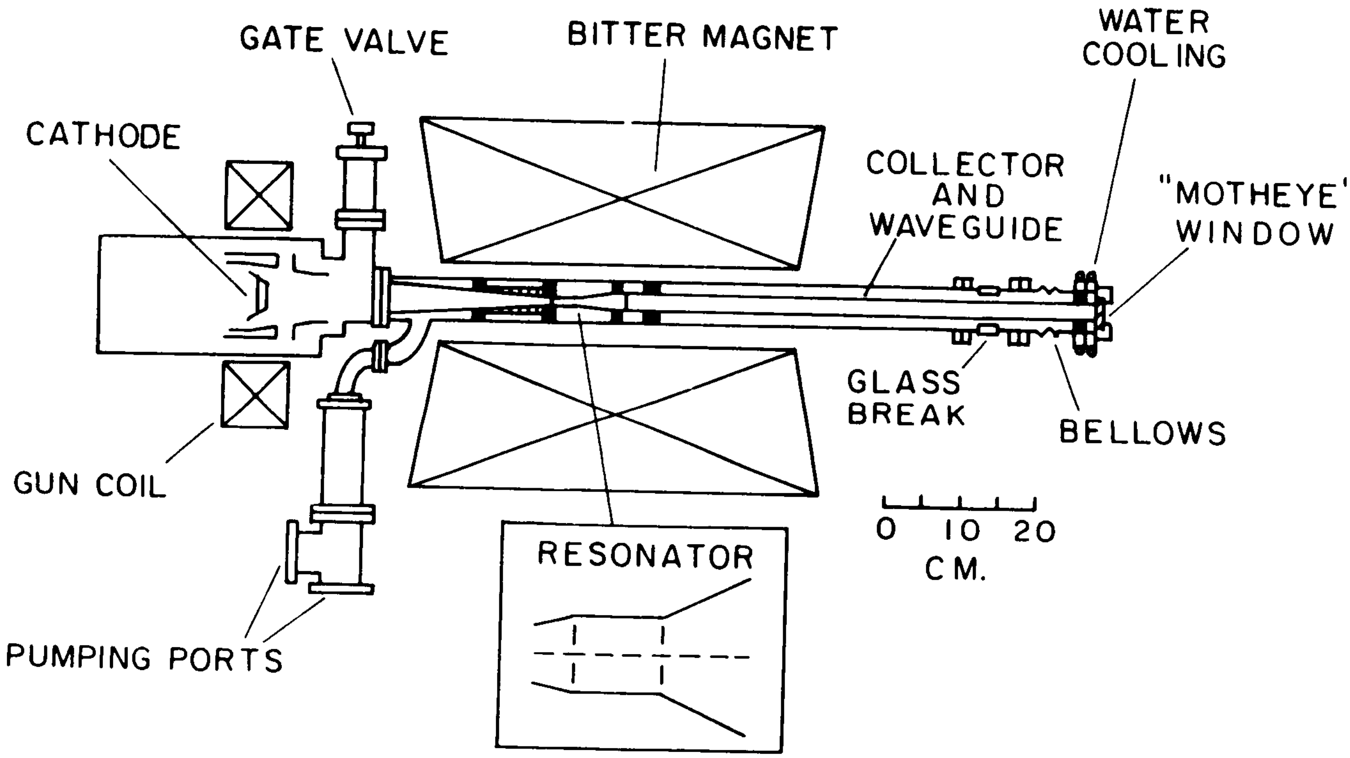
* **Phase locking the tube**

A commercially available gyrotron is the 140 GHz gyrotron manufactured by Varian. This operates in the TE_{03} mode and has generated a power of 100 kW in CW operation. The graph shows a plot of rf power as a function of beam Voltage. At 60 kV, a power of 100 kW was achieved (ref 1).

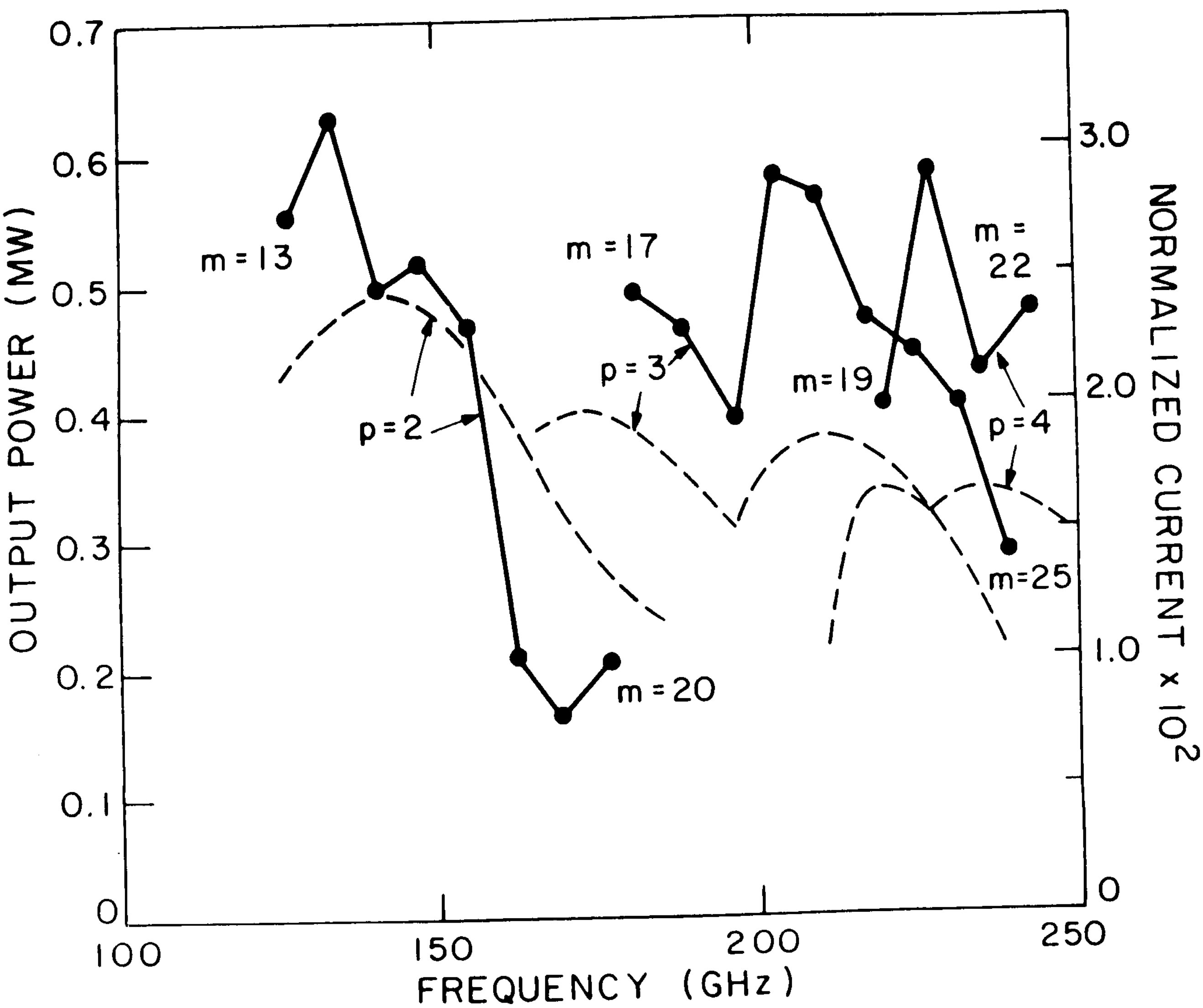


Output power versus beam voltage in pulse tests on the first experimental 140 GHz gyrotron for a beam current of 6 A.

A schematic of the MIT 140 GHz gyrotron. This gyrotron operates in high order whispering gallery modes, and at optimum performance has achieved a power of more than half a Megawatt. It operates in a pulsed mode with pulses about 4 μsec long (ref 2).

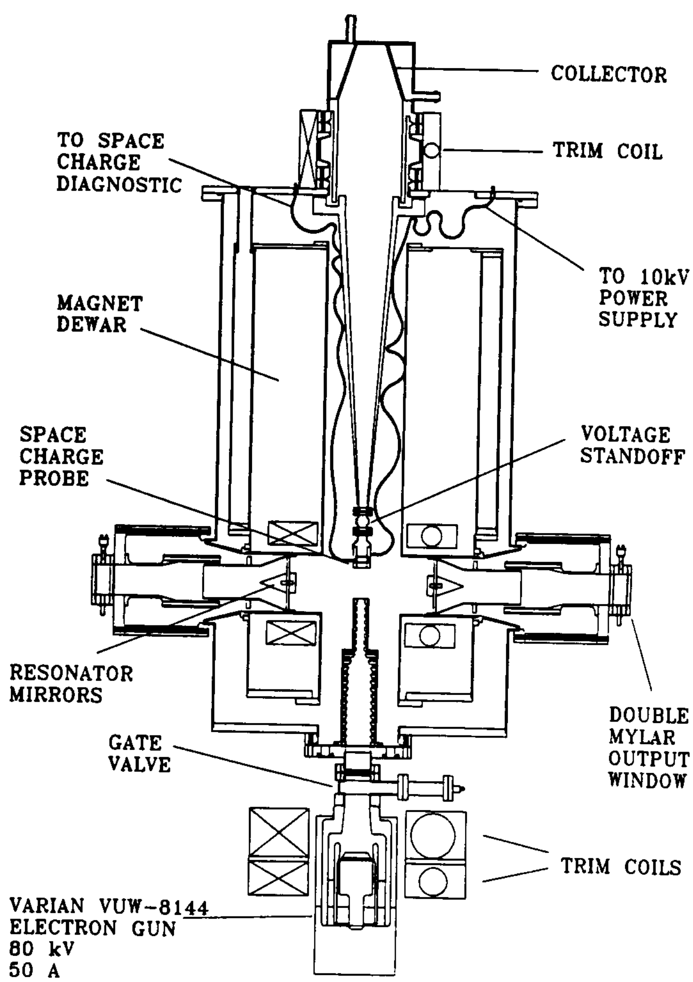


A plot of the power as a function of frequency for the MIT gyrotron. As the magnetic field increases, the gyrotron hops first along a series of TE_{m2} modes, then along a series of TE_{m3} modes, and finally along a series of TE_{m4} modes.



A schematic of the NRL quasi-optical gyrotron. The radiation is confined by a series of resonator mirrors aligned horizontally. The electron gun injects a beam vertically, and when it traverses the resonator, it gives up some of its power to modes in the resonator at the cyclotron frequency or its harmonics. The radiation is extracted by diffraction around the edges of the resonator mirrors. NRL contends that as the frequency of the radiation increases, optical rather than microwave techniques will become more and more important. The quasi-optical gyrotron is a first step in that direction (ref 3).

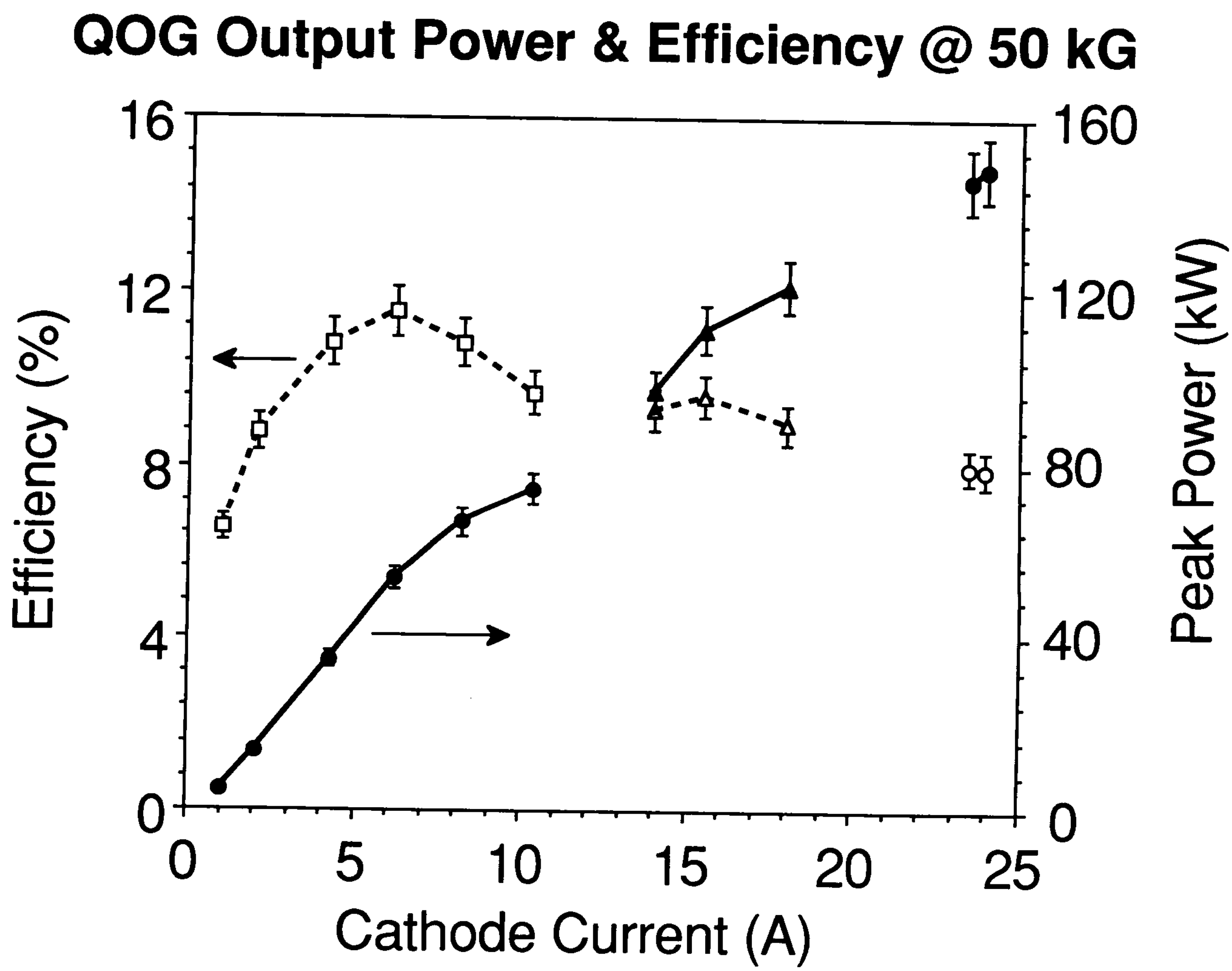
NRL HIGH POWER
QUASI-OPTICAL GYROTRON



Advantages of the QOG for Megawatt CW operation at 100-300 GHz

- Resonator and interaction volumes are large ($>>\lambda^3$).
- Low resonator mirror losses (ohmic).
- Low electron beam energy (~ 100 keV).
- Effective transverse mode selection.
- Moderately insensitive to electron beam temperature.
- Radiation output coupling is independent of interaction length.
- Radiation output and e-beam collection are separated.
- Tunable output frequency.
- Allows use of dc electric field for efficiency enhancement and space-charge cancellation.

The power and efficiency of the NRL Quasi optical gyrotron as a function of cathode current. The operating frequency is 130 GHz.



Phase control can be achieved either by running in an amplifier or phase locked oscillator mode. In either case a source is needed to drive the system. Currently available sources are extended interaction oscillators (EIO's) and extended interaction amplifiers (EIA's), manufactured by Varian, Canada. Their output powers are about the same, but so far, EIO's exist at higher frequencies. EIA's have gains of about 30 dB.

Available CW EIA's

VKB 2463T	**95 GHz**	**50 W**

Electronic tuning range = 0.15%

Available CW EIO's

VKB-2426L,M	**95 GHz**	**50 W**
VKB-2438L,M	**140 GHz**	**20 W**
KKY-2432L,M	**300 GHz**	**1 W**

Electronic tuning range = 0.15%
Mechanical tuning range = 2 GHz

The amplifier can be driven by an impatt diode at 20 mW. All phase control can be done at 20 mW power level.

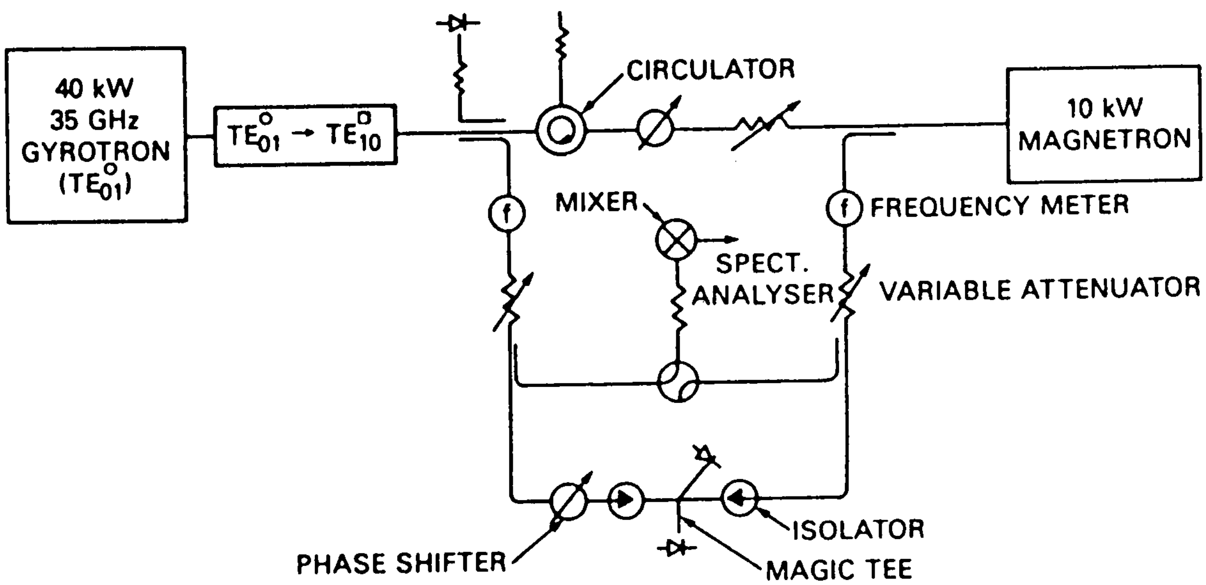
Amplifier would require more than 40 dB gain at 140 GHz, and more than 55 dB at 300 GHz.

Adler's relation for phase locking bandwidth of an injection locked oscillator:

$$\Delta f/f = 1/Q\,(Pin/P_{out})^{1/2}$$

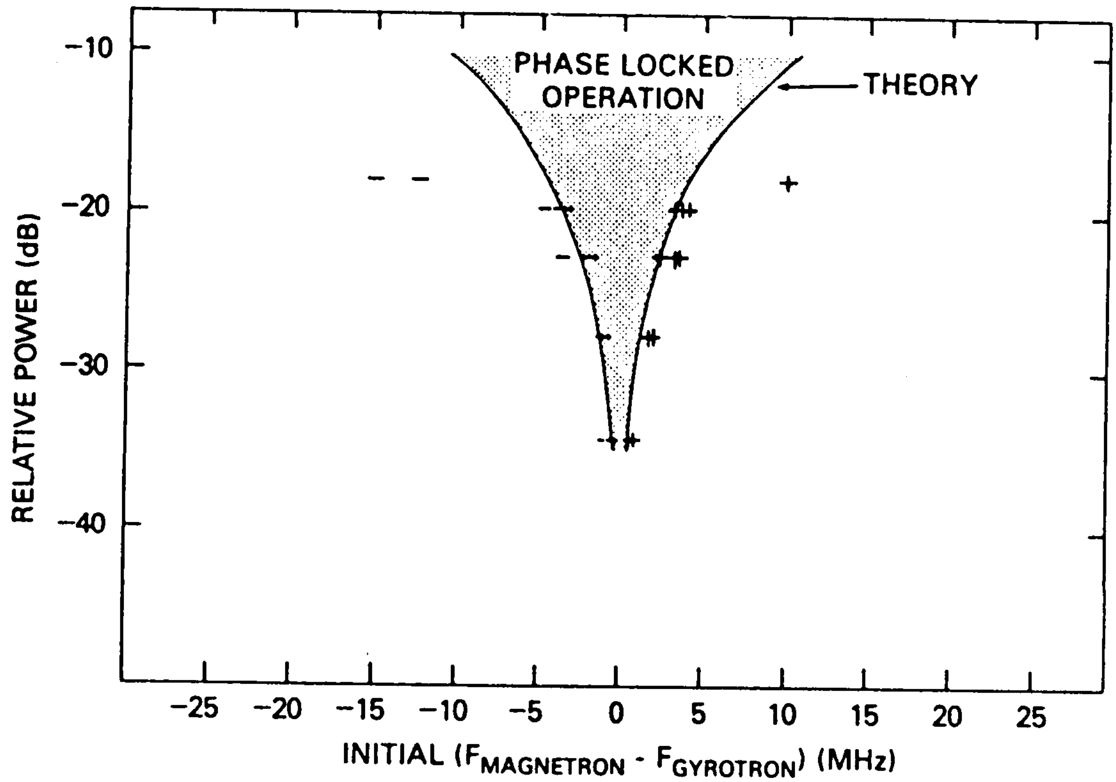
Large gain can be achieved, but operation must be very near the natural frequency.

A schematic of the NRL 35 GHz phase locked gyrotron oscillator experiment. The gyrotron ran in a low order (TE_{01}) mode. The locking signal was injected through a circulator into the output waveguide. The gyrotron operated at about 20 kW. The locking bandwidth was measured as a function of the magnetron power. The relative phase of the two signals was measured with a magic Tee hybrid coupler. Also the power spectrum was measured for the free running oscillator as well as the locked oscillator (ref 4).



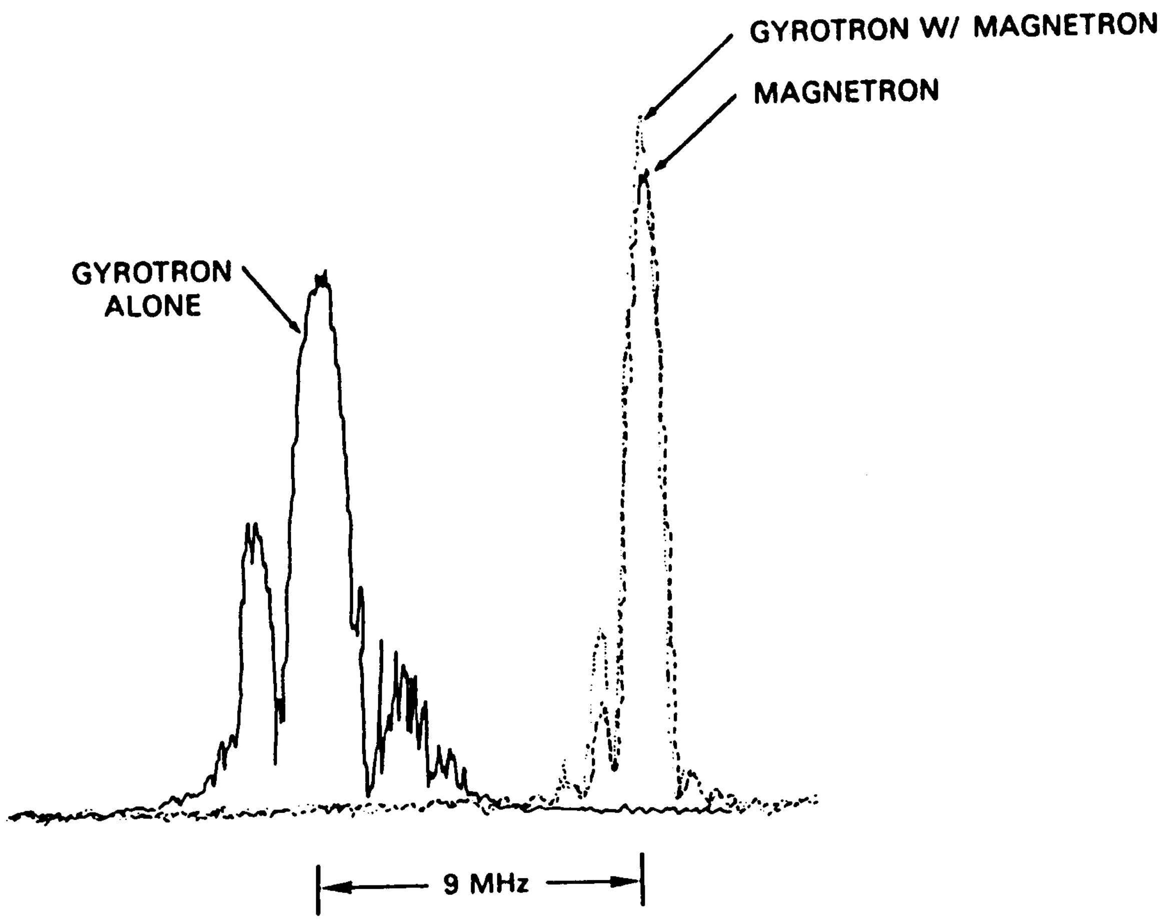
Line drawing of the experiment.

An experimental measurement of the region of phase locked operation of the NRL phase locked gyrotron compared with the relative power of the gyrotron and magnetron. The solid line is Adler's theory. Notice that the agreement is reasonably good.



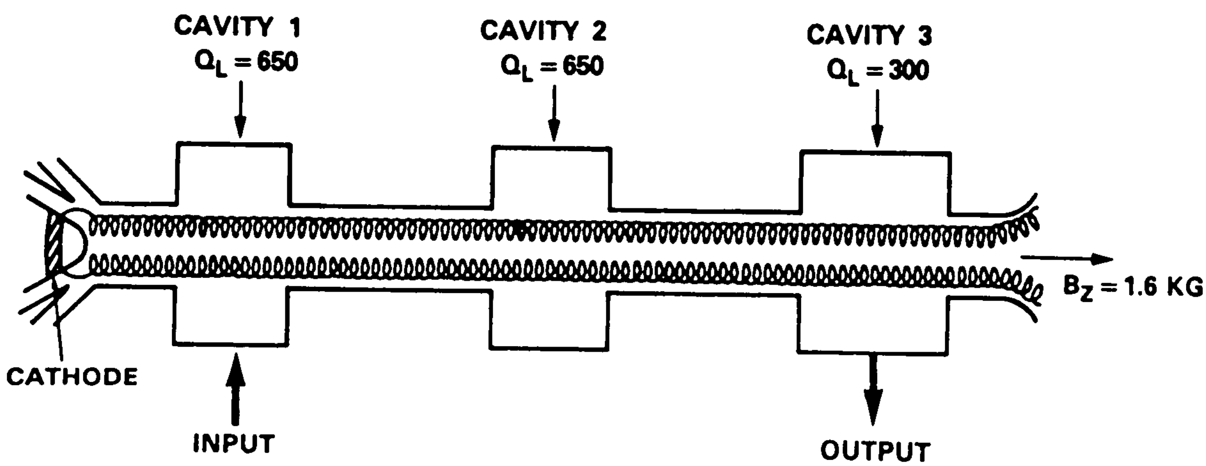
Maximum frequency separations over which phase locking was observed as a function of relative drive power. The gyrotron and magnetron powers were those in the TE_{01} (circular) mode at the output window of the gyrotron.

To be sure that the magnetron was locking the gyrotron and not visa versa, the spectrum of the gyrotron and magnetron in the free running mode was taken. Notice that they are quite different. When the gyrotron runs in the phase locked mode, its spectrum matches that of the magnetron.



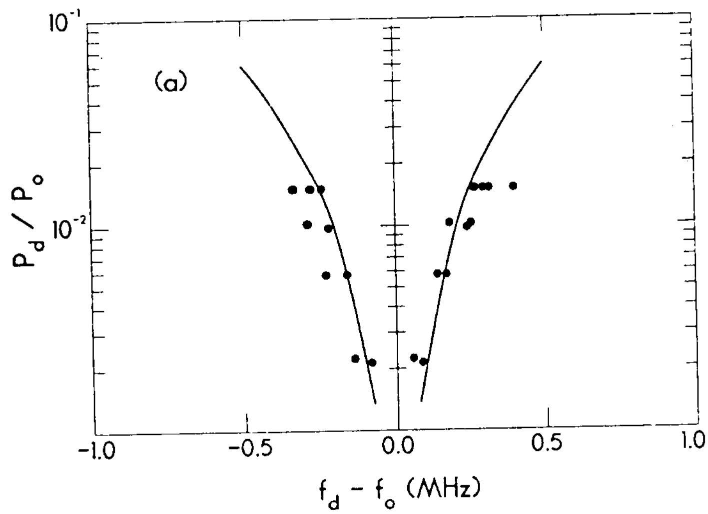
Spectra of the gyrotron, in locked and unlocked operation, as compared to the magnetron spectrum. The magnetron power was 15.5 dB below that of the gyrotron.

The locking bandwidth can be considerably increased by utilizing one or more prebunching cavities to prebunch the beam instead of utilizing direction through the output. Shown is a schematic of another NRL experiment of a phase locked gyrotron utilizing a prebunched beam. This oscillator ran in fundamental mode at 4.5 GHz and at power levels of 1-2 kW (ref 5).

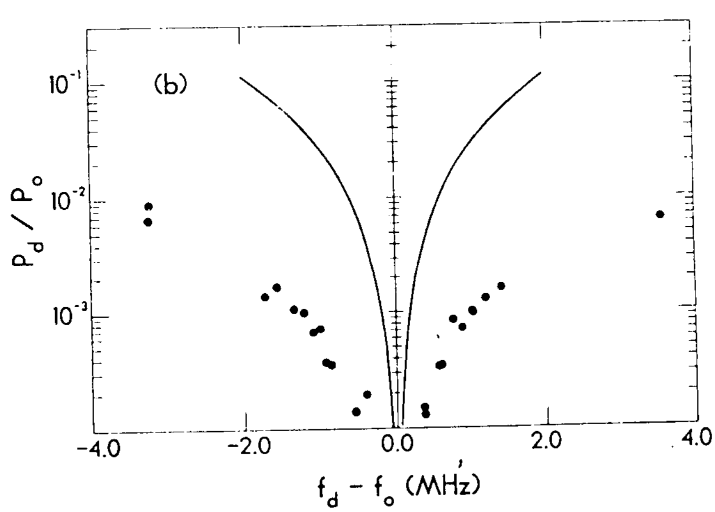


Three-cavity gyroklystron configuration. The first two cavities are 6.06 cm in length, and the third is 7.4 cm. The connecting drift spaces are 10.1 cm long.

Plot of locking bandwidth for direct injection from Ref 5 is shown on top. It agrees well with Adler's theory. Shown on the bottom is the locking bandwidth for the case of a prebunched beam. Notice that the locking bandwidth is considerably larger than that predicted by Adlers theory.



(a)

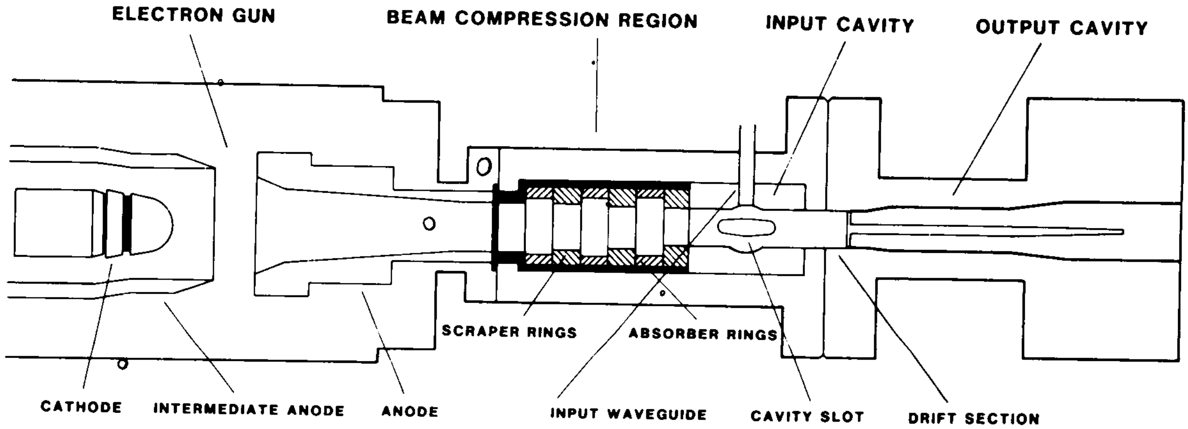


(b)

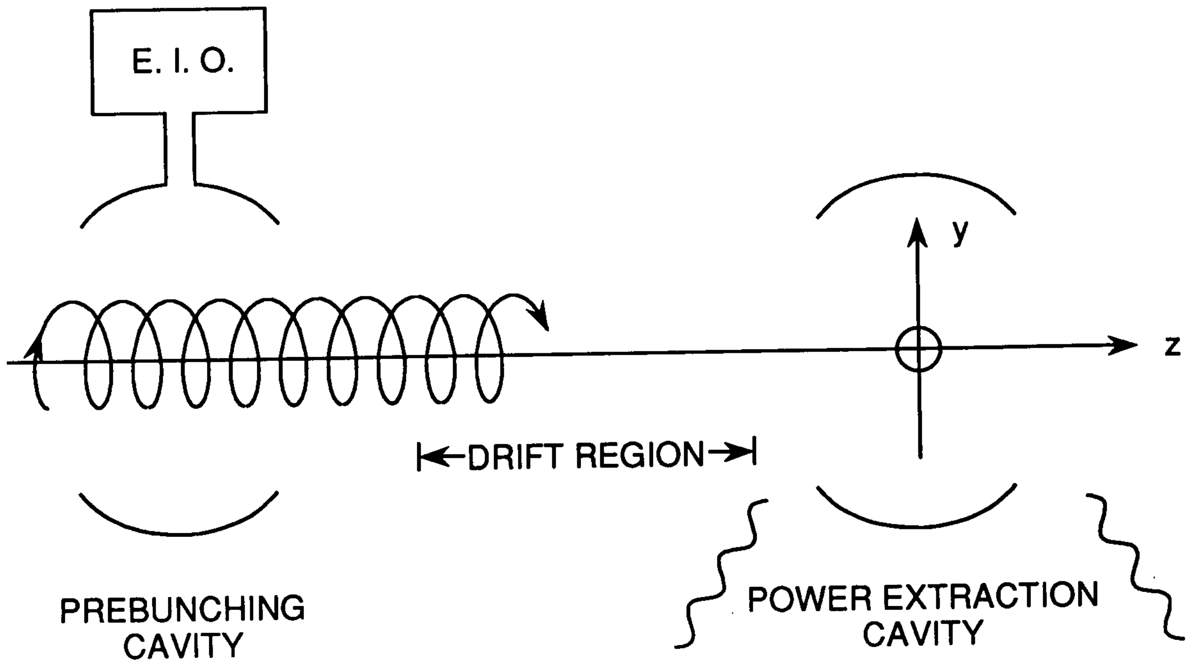
Phase locking bandwidths for (a) direct injection of cavity 1 with $Q_e = 1100$ and (b) three cavity configuration with Q_e = 375 in cavity 3. Note that the locking bandwidth exceeds the theoretical prediction (solid curves), in the multicavity case.

As the frequency and power get larger, one must ultimately deal with overmoded or optical systems. A TE_{13} phase locked gyroklystron has been designed and partially constructed at NRL, but has not yet run (ref 6).

PHASE-LOCKED GYROKLYSTRON OSCILLATOR



A prebunching cavity can be mated to the NRL quasi-optical gyrotron. This will allow investigation of phase locking the quasi-optical gyrotron. This experiment is in the planning stage.



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